Optimization of Pulse Duration and Pulse Charge During Transcutaneous Electrical Nerve Stimulation

The main effects and interaction of pulse duration and pulse charge on sensory, motor and painful stimulation were examined on six male subjects. Surface electrodes were placed over the triceps brachii muscle. Pulse duration was varied between 5 and 1000 μs. Peak current, muscle torque and four excitatory responses were determined. Sequential order of sensory, motor and painful stimulation was evidenced. Selective excitation of these different physiological responses was easier and required less charge as pulse duration became shorter. The greatest non-painful torque was reached at 100 μs pulse duration. The most suitable range for motor stimulation was 20 to 200 μs. For painful stimulation, a 5 to 10 μs duration was favoured. A range of 20 to 100 μs was recommended for sensory stimulation.

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Many years of practical, experimental and theoretical testing of Transcutaneous Electrical Nerve Stimulation (T.E.N.S) have yielded an enormous amount of useful data (Benton *et al* 1981) Progress has been characterized by much more rapid development of clinical application than in determining optimal parameters required for such application. Selecting criteria associated with patient safety has also been neglected to some degree (Cooper *et al* 1977, Seligman 1982).

The advancement of electrophysiology, particularly with reference to excitation of peripheral nerves, has revealed many phenomena which affect both the physiological and clinical responses to the application of T.E.N S. (Burton and Maurer 1974). Among the more reproducible physiological responses is the ability to excite sensory, motor and pain-conducting fibres. Isolated excitation of each of these three different nerve groups may be easier to obtain with short duration pulses, as can be deduced from the Strength Duration (S-D) curves reported by Li and Bak (1976) and Howson (1978)

Thus, one can classify the main physiological responses of the excitatory system as sensory, motor and painful stimulations. Each can be used to achieve a desired clinical result. In the area of physical medicine and rehabilitation, these clinical responses include pain modulation, oedema reduction, muscle re-education, elimination of protective muscle spasm, normalization of muscle tone following spasticity, maintenance or improvement of joint mobility and hastening tissue healing.

Selecting an optimal treatment is therefore a complex task. Optimization of the electrical parameters, physiological responses, treatment techniques and clinical responses in different physical impairments must all be evaluated for their main effects as well as their interactions.

Deciding on suitable electrical parameters to achieve a physiological response has been the focus of a number of investigations. In particular, the optimal pulse duration for an ultimate motor response was studied by several researchers. Crago *et al* (1974) could not draw definite conclusions as to the best pulse duration for eliciting excitation from the finger flexors. Peckham *et al* (1975) preferred 100 μs for the same group of muscles, whereas Bowman (1980) found a 300 μs pulse duration optimal for stimulating the Quadriceps Femoris muscle. Different muscle groups were recently tested by Moreno-Aranda and Seireg (1981) for their motor, non-painful response. Favourable results occurred with a 10,000 Hz pulse frequency which corresponds to a 50 μs duration per phase.

Optimization of pulse duration for sensory stimulation was investigated by Howson (1978). Very short pulses, between 10 and 50 μs seemed preferable because of a better ability to differentiate the sensory from the motor and painful stimulation. Conversely, for a painful response, the optimal pulse duration was shown by Notermans (1966) to be 5 ms.

Most of these representative studies did not include data on pulse charge which is now regarded as an important factor in terms of the safety of stimulation (Seligman 1982, Crago *et al* 1972, Linzer and Long 1976). From available data, a conclusion can be reached that the shorter the pulse, the lower the charge necessary to obtain threshold stimulation of all types of excitatory responses (Crago *et al* 1972 Gracanin and Trnkoczy 1975, Dooley *et al* 1978). However, whether minimal pulse charge results in optimal excitatory responses and provides the best sensory, motor or painful stimulation is an important question to which no answer could be found in the literature.

The purpose of the present study was to examine the main and interaction effects of pulse duration and pulse charge on sensory, motor and painful stimulation. Particular attention was paid to pulse charge density, its magnitude during the attainment of the various excitatory responses and its relevance to the safety of stimulation.

Other electrical parameters such as uniphasic versus biphasic, pulse shape, pulse frequency and pulse train along with their effects on the physiological responses were beyond the scope of the present study.

Method

Of the six healthy male subjects who volunteered to be tested, three had experienced electrical stimulation and three had not The target region was the dorsal side of the left arm. Stimulating electrodes were secured over the motor points of the medial and lateral heads of the Triceps Brachii muscle. The electrodes were made of carbon impregnated sponge and their 2×2 cm size presented an area of 4cm²

A subject was seated with his shoulder at 90° abduction, his elbow at 90° flexion, and his forearm in mid-position — between supination and pronation. A specially constructed arm rest allowed for this position and included a strain-gauge system to measure the extension torque produced by the Triceps during motor stimulation. The arm and forearm were fastened firmly to the mechanical system to minimize movement between the latter and the limb.

The stimulator was a laboratory prototype constant current generator with a pulse duration adjustable from 0.5 to 1000 μs. Pulse shape was a monophasic square wave with a maximum intensity of 500 mA. Pulse rate was fixed at 20 pulses per second

Stimulation protocol included measuring S-D curves for each of four physiological responses: 1) threshold of sensory stimulation; 2) threshold of motor stimulation; 3) threshold of painful stimulation, which represented the strongest muscle contraction without pain; and 4) maximal tolerance level of painful stimulation. Pulse duration was varied at logarithmic intervals from 5 μs to 1000 μs with the intensity being adjusted to achieve each of the four physiological responses. Pulse charge (Q) was calculated as a product of current intensity and pulse duration. Torque measurements were recorded from the strain-gauge output

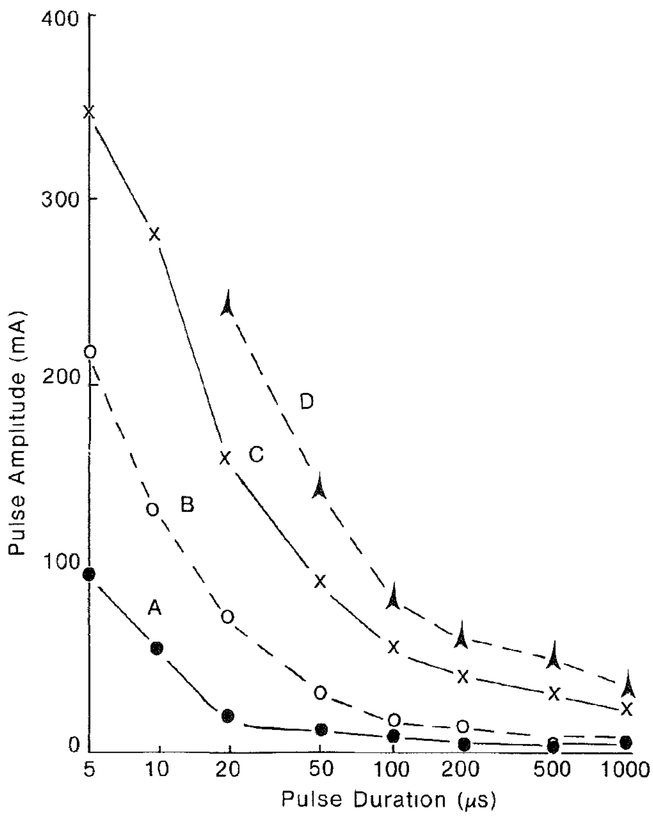

Figure 1: Strength Duration Curves of the four major excitatory responses (A) sensory threshold, (B) motor threshold, (C) pain threshold, (D) maximal tolerable pain response

Results

A mean peak current necessary to achieve the aforementioned physiological responses at each of eight pulse durations is illustrated in Figure 1 As can be seen, there was an insufficient current output to reach a maximal pain sensation at 5 and 10 microseconds An important observation is that at each pulse duration there was a sequential order of threshold excitation starting with sensory, followed by motor and ending with stimulation of the pain-conducting fibres.

In addition to the threshold intensities of each of the three groups of nerves, the four curves present three important intensity intervals which represent minimum to maximum ranges of stimulation intensity for each of the three types of excitatory responses. As evidenced, the largest interval occurs between the motor and pain responses. The range of tolerable pain responses is somewhat smaller and the smallest range is that between sensory and motor stimulation.

Intervals at each pulse duration can be calculated as the absolute difference of intensity or as percent change Absolute and percent differences between motor and sensory thresholds and between pain and motor thresholds are graphed in Figure 2 and Figure 3, respectively. Whereas it is very clear that absolute differences increase as the pulse duration becomes shorter, the percent changes do not seem to follow a specific pattern. Figure 3 may offer a trend, but statistical testing of its existence may not be warranted due to the small sample size.

Figure 4 depicts that eliciting a painful response may require increasing intensity nearly 800 percent beyond sensory stimulation At 5-10μs, a relatively small increase in the current needed for sensory stimulation may evoke a painful response. Longer pulse durations exhibit a much greater increase of intensity before painful sensation is reached. These observations suggest that a pulse duration of 20 μs or longer should be selected when sensory stimulation alone is being sought.

Pulse charge as a function of pulse duration is plotted in Figure 5 for each of the four physiological thresholds. A sharp increase of charge was required to achieve each of the physiological excitations above 200 μs. On the other hand, it is clear that the shorter the pulse, the less charge was required to obtain the four physiological responses.

Charge density, calculated as charge per cm^2, is recorded in Table 1. Mean values for the six subjects ranged from a minimum of 0.12 μC/cm^2 to 8.45 μC/cm^2 and were well within safety boundaries.

Figure 6 combines the charge of the maximal non-painful elbow extension torque and the Charge Torque Ratio (CTR) both as functions of pulse duration As seen, the optimal pulse duration necessary to generate the largest torque was 100 μs. But, relative to the amount of charge, the 20 μs pulse duration required the least charge per unit torque. In general, the middle interval (between 20 and 200 μs) appears preferable for motor response generation to the interval between 5 and 20 μs or the interval between 200 and 1000 μs.

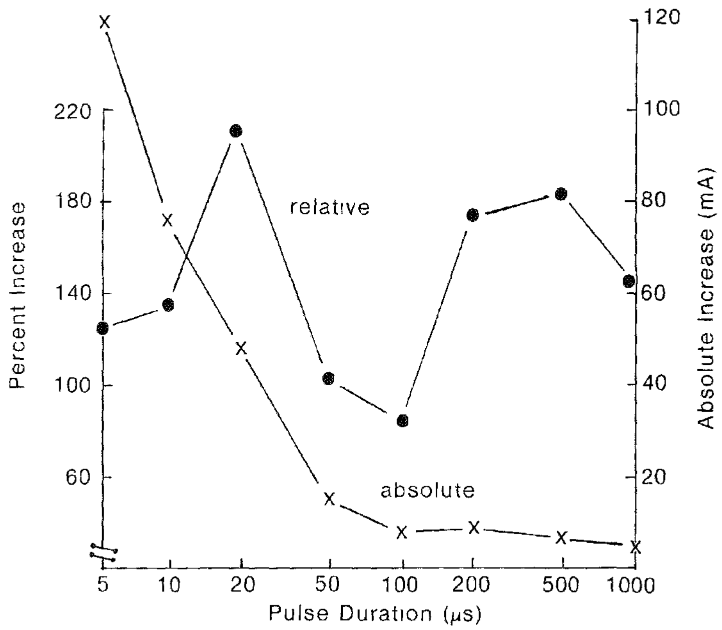

Figure 2: Absolute and percent differences between motor versus sensory thresholds

Discussion

The S-D curves obtained in the present investigation reproduced the basic relationships between pulse duration and current intensity found in the literature (Li and Bak 1976, Crago *et al* 1974, Moreno-Aranda *et al* 1981). The inability to stimulate pain-conducting fibres at 5 and 10 μs pulse duration is probably due to an insufficient current source. At these durations, the maximum of 500 mA and the electrode area of 4 cm^2 could

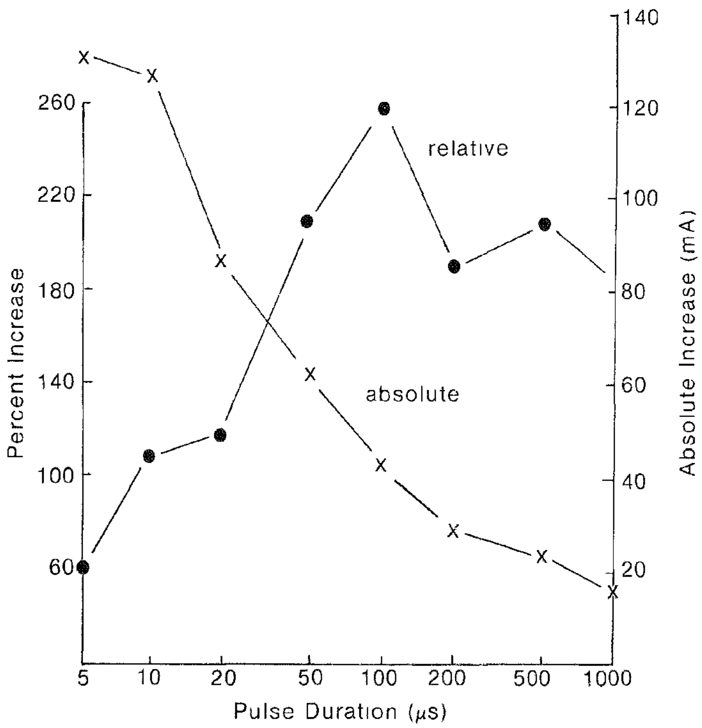

Figure 3: Absolute and percent diffences between pain versus motor thresholds

only result in a maximal pulse charge density of 0.62 μC/cm² and 1.2 μC/cm² for 5 and 10 μs pulse durations respectively These charges were sufficient to elicit maximal painful response from only two of the six subjects.

The hypothesis of a sequential order of stimulation where sensory fibers are excited before motor fibres and the latter before pain-conducting fibres is strongly supported by the present data Sensory and motor fibres are the largest in diameter and their conduction velocity the fastest (Benton *et al* 1981, Li and Bak 1976) They require the least amount of electrical charge to become depolarized. Thus, at any given pulse duration, both sensory and motor fibres are most likely to be the first to respond to the electrical stimulation. Of the two, sensory response precedes because these fibres are likely to be closer to the stimulating electrode when surface stimulation is applied. Likewise, excitation of motor fibres should precede the pain-conducting fibres as long as both types are at close proximity under the electrode. Although the latter fibres are usually more superficial than the former, their smaller diameter and much higher resistance to current flow makes their excitation characteristics inferior to motor fibres.

Selective excitation of the different physiological responses was shown to be easier as pulse duration became shorter. Howson (1978) reported similar results. However, finding that the percent change is not necessarily the greatest at the shortest pulse duration contradicts Howson's data.

Table 1:
Charge density (μC/cm²)

	5μs	10μs	20μs	50μs	100μs	200μs	500μs	1000μs
Sensory stimulation	0.12	0.14	0.11	0 18	0.22	0.28	0 51	0.87
Minimal motor stimulation	0 27	0 33	0.36	0 37	0.41	0.77	1.47	2.12
Maximal motor stimulation	0.43	0.69	0.80	1 14	1.47	2 23	4 50	6.12
Maximal painful stimulation	*	*	1.20	1 72	1 97	3.16	6 38	8 45

*Insufficient charge for these short pulse duration.

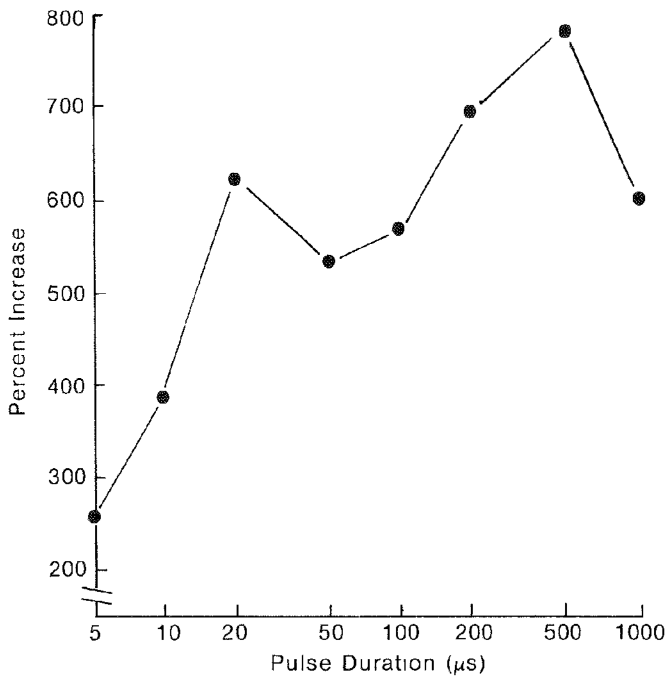

Figure 4: Percent differences between pain versus sensory thresholds

Among the reasons for this discrepancy, one may consider methodological differences such as pulse characteristics, electrode size and electrode position — all of which may affect the results (Linzer and Long 1976, Wolf *et al* 1978). This information was not disclosed by Howson, whose data was obtained from a single subject and should therefore be considered with some reservation.

The present results imply that the ability to selectively stimulate the different nerve types at short pulse duration may not be a physiological phenomenon but rather a technical problem. If one desires an accurate selectivity at a longer pulse duration, the generator should have a vernier control so that smaller, more sensitive adjustments of intensity could be made.

Optimization of pulse parameters to achieve maximal physiological responses may be based on several assumptions. One is that pulse charge density must not exceed 20-100 $\mu C/cm^2$ so that the stimulation would be safe (Seligman 1982). Within the limits of the present study, the maximal and minimal charge densities were 8.45 $\mu C/cm^2$ and 0.12 $\mu C/cm^2$ for the most painful and least sensory stimulation, respectively. Thus, the entire range of physiological responses was achieved well within the limits set for non-harmful stimulation

A second question of interest is whether pulse charge should preferably be kept at minimum for each of the four major excitatory responses so that the stimulation would be most efficient. The tendency of the electrical charge to decline with the shortening of pulse duration was evident for the sensory, motor and painful stimulation. One would then like to hypothesize that 5-10 μs pulse duration would be optimal for all the excitatory responses. The hypothesis is most probably false, at least in regard to motor stimulation.

Gracanin and Trnkoczy (1975) found also that pulse charge declined as pulse duration was shortened, but illustrated that at less than 100 μs the charge rose again. In their study, current intensity was increased until a predetermined, constant muscle torque was generated even if the stimulation became painful. In the present investigation, muscle torque was not constant Rather, it was measured at the point of beginning of pain so that muscle torque was maximal but without pain. Direct comparison of the two investigations can be made by looking at the Charge Torque Ratio (CTR). Evidently, the amount of charge per unit torque also increased at 5-10 μs pulse duration, thus showing agreement with Gracanin and Trnkoczy findings.

Examination of the torque-pulse duration relationship, irrespective of charge suggests that the optimal value for elbow extensors should be around 100 μs pulse duration Peckham *et al* (1975) preferred the same value for the finger flexors. Examining a similar question on the Quadriceps Femoris muscle led Bowman (1980) to prefer a 300 μs pulse duration. This seems to be slightly out of the optimal range reported herein. It is possible that various muscle groups have different optimal pulse duration and the difference in the sexes of the subjects in the two studies may have also contributed to the varying results. Finally, the present study included a wide range of pulse durations, whereas Bowman and his associates compared only 50 and 300 μs and may have missed optimization at 100 or 200 μs.

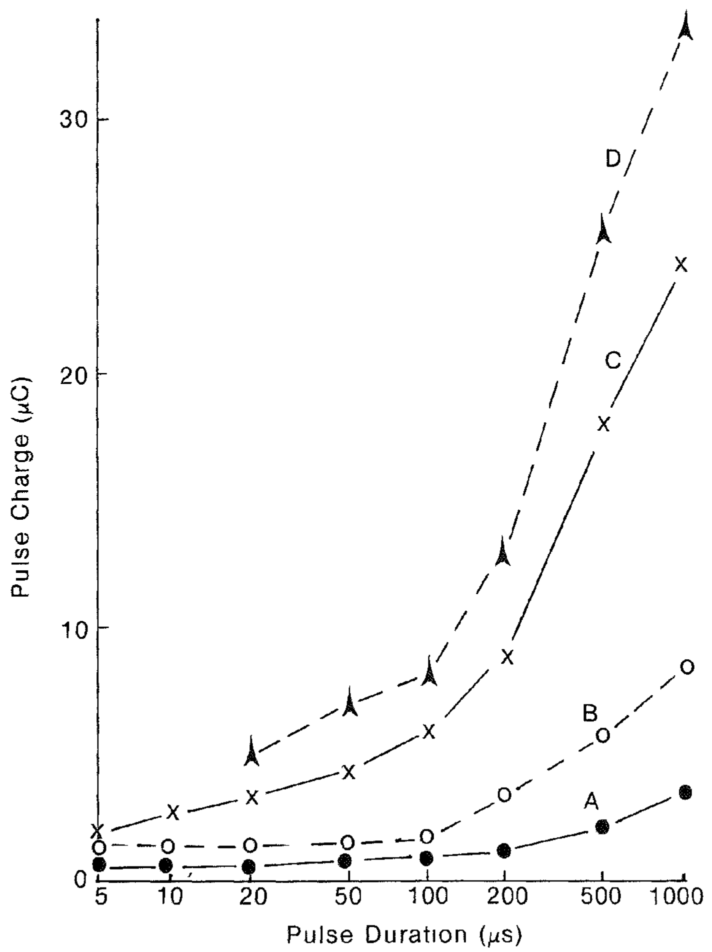

Figure 5: Pulse charge and pulse duration relationships for the four major excitatory responses (A) sensory threshold; (B) motor threshold, (C) pain threshold, (D) maximal tolerable pain response

The foregoing results and discussion may lead to the general conclusion that a range of 20 to 200 µs pulse duration is most suitable for motor stimulation. In this range, the CTR is low while the maximal motor response without pain is still only moderately different from maximum. Above 200 µs a significantly greater pulse charge is required and a similar increase in CTR occurs. This indicates that the range is less suitable for motor stimulation. The 5-10 µs range is also undesirable due to the increase of the CTR which is evidenced.

Painful stimulation is sought for some clinical applications such as acupuncture points in chronic low back pain (Fox and Melzack 1976, Mao *et al* 1980). Within the range studied, 5 µs gave painful stimulation with minimum pulse charge and thus increased the subject's safety. Furthermore, at this pulse width pain response was achieved with the least amount of muscle torque. Since motor response is not required during trigger-point stimulation, it can be minimized by using very short pulses.

During the experiment, all six subjects reported that the quality of pain perception was distinctly different between the very short pulses and the very long pulses. The former was a sharp, pain prick while the latter was a burning pain sensation. These statements agree with those reported by the subjects in Notermans' study (Notermans 1966). At present, the effect of different types of painful stimulation on clinical results is not known. Thus, within the limits of the present data and discussion, it may be proposed that the shortest pulse duration should be favored, provided that sufficient peak current and charge density accompany such pulse duration.

Sensory stimulation is widely and successfully used to achieve pain modulation in a variety of medical conditions. Two examples are the works of Hymes *et al* (1974) and Solomon *et al* (1980). Linzer and Long (1976) suggested 50-100 µs as suitable for sensory stimulation, but did not test shorter than 50 µs pulses. Present results demonstrated that sensory responses were obtained throughout the studied range. Considering only the minimal charge criterion, the 5-20 µs is the best range for pulse duration. However, if one wishes to achieve sensory stimulation without motor or pain responses, then the ratios of motor over sensory and painful over sensory charges should be maximized. No obvious maximum was apparent for the former, whereas the latter is greatly improved above 20 µs. Since

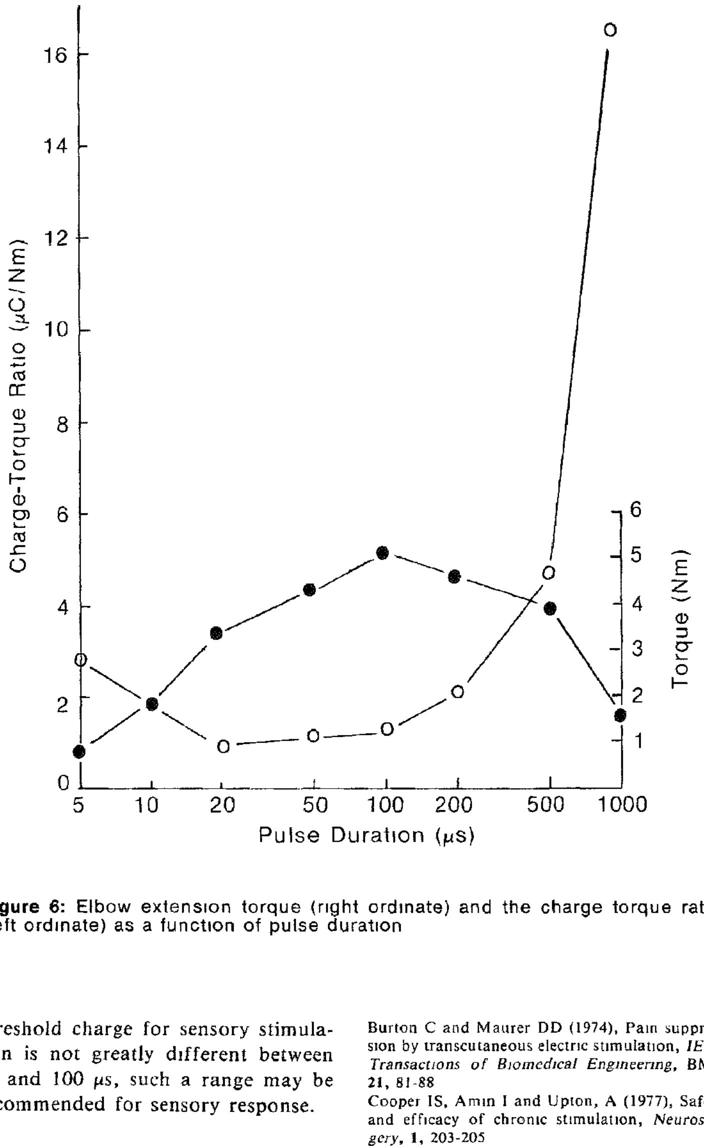

Figure 6: Elbow extension torque (right ordinate) and the charge torque ratio (left ordinate) as a function of pulse duration

threshold charge for sensory stimulation is not greatly different between 20 and 100 μs, such a range may be recommended for sensory response.

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